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TECHNICAL NOTE

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A FLIGHT DETERMINATION OF THE ATTITUDE CONTROL POWER AND DAMPING REQUIREMENTS FOR A VISUAL HOVERING TASK IN THE VARIABLE STABILITY AND CONTROL X-14A RESEARCH VEHICLE

By L. Stewart Rolls and Fred J. Drinkwater III

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The variable stability and control X-14A research vehicle with various combinations of control power and damping was evaluated by three pilots during hovering under visual control at altitudes up to 50 feet and in winds up to 10 knots. Although only limited ranges of control power and damping were available, it was possible to investigate satisfactory combinations of these about all three axes. The boundaries for satisfactory and unacceptable control power and damping characteristics determined in flight are compared with those obtained on a piloted motion simulator.

INTRODUCTION

The National Aeronautics and Space Administration has for many years investigated the handling qualities requirements for aircraft and the studies have been extended to vertical take-off and landing types of aircraft while hovering. To determine the control power and damping requirements for these aircraft, studies have been conducted on a variable-stability helicopter (ref. 1) and on moving base piloted simulators (ref. 2). The existing specifications for fixed-wing aircraft and helicopters were closely examined to derive a proposed set of requirements for V/STOL type airplanes (ref. 3).

It was felt that the pilot's workload in the hovering mode of a VTOL airplane would be different than that in a simulator or a helicopter. Therefore, boundaries for satisfactory and acceptable control characteristics were investigated in the Bell X-14. This deflected jet VTOL test bed was modified to provide a variable-stability and control system capable of changing the basic airplane control power and damping over a limited range. Three test pilots participated in the flight investigation designed to map the satisfactory and acceptable regions of control power and damping at zero attitude stability while hovering near the ground but out of ground effect. This report presents these boundaries and compares them with published piloted simulator results.

DESCRIPTION OF AIRPLANE

The Bell X-14A VTOL test bed aircraft used in this investigation is a fixed wing, jet-propelled, deflected-jet vehicle. The exhaust from the jet engines passes through cascade-type diverters which enable the pilot to select vertical or horizontal thrust. During hovering, control of the airplane is maintained by the use of reaction jets at the wing tips and the tail. The air for these reaction controls is bled from the compressors of the turbojet engines. A complete description of the original X-14 is presented in reference 4.

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To create a vehicle on which a study of the control-power and damping requirements of a hovering aircraft could be conducted, the stability and control of the X-14 were made variable. The modified airplane, the X-14A, is shown in figure 1 in hovering flight. To provide this variable stability and control, it was necessary to replace the original jet engines with General Electric J-85-5 engines which produced greater amounts of thrust and furnished greater quantities of bleed air for the reaction controls. In the modification, the existing set of mechanically linked reaction control nozzles was retained to serve as the pilot's basic control system, and an additional set of electric servo-driven nozzles was added to provide variations in airplane damping and control power. At present, the pilot's system has 10 percent more control power than the variable-stability system. The variable-stability and control system contains four nozzles: one at each wing tip for roll control, and two at the tail to produce pitch and yaw motion. The size of the port on each of these nozzles, and hence the magnitude of the force on the airframe, is determined by the output of an electric servomotor. A simplified block diagram illustrating the control for one of the variable-stability nozzles is presented in figure 2. The control circuitry is identical for the other nozzles. This diagram shows that during the investigation, the reaction jet force was determined from the sum of four different signals consisting of three rate-gyro outputs and the pilot's control displacement. The output of the gyro that measured angular rate about the axis investigated produced a signal which was coupled to the nozzle corresponding to that axis, while the other two gyros caused a cross-coupling motion, used in this case, to eliminate the gyroscopic cross coupling due to the jet engines. As indicated on the block diagram (fig. 2), the pilot can use the potentiometers to adjust the magnitude and sign of these input signals. The pilot's control panel in the cockpit is shown in figure 3. In the investigation, angular-rate signals were used to position the nozzles to oppose airplane motion in direct proportion to the angular velocity, thus creating rate damping while the response from the pilot's control signal either supplemented or opposed the basic airplane reaction nozzles, thus changing the amount of control power.

During the development of the variable-stability system, tests conducted on a two-axis motion simulator indicated that the pilot would have difficulty detecting a failure of a reaction nozzle in sufficient time to apply corrective control before reaching an unsafe attitude. To avoid dangerous attitudes, an error detection circuit was included in the variable stability electronics which monitored the signals commanding the servomotors. If this command signal differs greatly from the actual nozzle position, the electric power to the servomotor is shut off and the nozzle centers by action of the reaction jet forces.

A The X-14A during these tests weighed 3200 pounds without fuel. The
6 maximum thrust for the hovering condition is about 3900 pounds. Character-
2 istics of the control system that might affect the evaluation reported
1 herein are:

Axis	Maximum control movement, in.	Friction, lb	Force gradient, lb/in.	Basic control power, radian/sec^2	Basic damping, 1/sec
Roll	±5	±2	0	0.8	-0.45
Pitch	±6	±1/2	0	.44	-.15
Yaw	±3	±5	0	.35	-.20

The pitch control contains a nonlinearity since in the last inch of stick travel there was only a small change in control power. This feature probably had little effect on the pilot ratings because it was beyond the normal range of stick motions.

The system providing variable control power and variable damping control was calibrated by measuring the airplane response to a series of step control inputs while hovering at 2500 feet altitude. A time history of a typical maneuver used during this calibration is presented in figure 4. The control power was determined from the magnitude of the angular acceleration at zero angular velocity multiplied by the ratio of total control deflection available to the control deflection used; the damping was determined from the rate of decay of angular acceleration with increasing angular velocity.

TESTS

The requirements of control power and damping for visual control were investigated while hovering out of ground effect and in generally calm wind conditions. The evaluation of the airplane in the hovering condition consisted of maneuvering at speeds up to 30 knots forward and rearward and 20 knots sideward, at altitudes up to 50 feet. Hovering turns, sidewise flight, and forward and rearward "quick stops" were performed to determine the effects of various combinations of control power and damping on the ability of the pilot to position the aircraft accurately and quickly over a ground reference point. Vertical take-offs and landings were also performed with each combination tested, and flights were made in winds up to 10 knots with no changes in the evaluation procedure. In general, the combinations of control power and damping were varied about only one axis at a time, while the characteristics about the other axes were usually kept near a value which the pilot rated acceptable.

In all the test runs, the pitch and yaw variable-stability nozzles were programmed to eliminate existing pitch-yaw coupling caused by the gyroscopic torque of the engines. Hence, the gyroscopic coupling effects on the controllability of the airplane were eliminated during this investigation. During these tests, normal throttle movements were required of the pilot to maintain height control and consequently some diligence was necessary to maintain height above the ground.

The results presented in this report are based upon the flight performance of three pilots. Two are NASA research pilots while the third is an Army test pilot, each with considerable flight experience in hovering helicopters and with other VTOL test bed aircraft.

RESULTS AND DISCUSSION

Control Power Versus Damping Boundaries

Control power and damping characteristics were evaluated during this investigation on the basis of the pilot opinion rating system described in table I and discussed in reference 5. Each of the three pilots rated a series of prescribed conditions with various amounts of control power and damping for each of the three airplane axes. The results are presented in table II. The difference between pilot ratings in table II is about a numerical rating of 1 for most conditions evaluated. Boundaries estimated from these ratings are presented in figures 5, 6, and 7. A numerical rating of 3-1/2 represents the boundary between satisfactory and unsatisfactory and a rating of 6-1/2 separates the unsatisfactory and unacceptable regions (see table I). A reasonable interpretation of these boundaries is that a control system of a VTOL airplane must be designed to fall within the satisfactory area regardless of the number of artificial augmentation devices necessary. However, failure of the augmentation devices must not result in a control system that falls outside of the satisfactory into the unacceptable region.

Establishing a 6-1/2 boundary for a VTOL aircraft in hovering flight is difficult, for it represents the minimum control power acceptable to the pilot and it is not desirable to spend much flight time in this configuration near the ground. For the purpose of this report, the 6-1/2 boundary was considered to be the highest control power and damping rated by any pilot. This boundary is not well defined because of the spread in the pilot ratings and the limited number of conditions rated. The 6-1/2 boundary for the pitch axis could not be determined because sufficiently low values of control power were not obtainable. The minimum value was about 0.4 radian per sec^2 and, as indicated on table II, the majority of the pilots rated this amount of control power as 5.

Examination of the boundaries shows that the pilots consider the lateral motions of the airplane the most critical because the greatest amounts of control power and damping are required about this axis. For the pitch and yaw axes, when the control power is above a value of about 0.5 radian per sec^2, the pilots consider extremely low values of damping satisfactory. With these low values of damping at the higher control powers, the pilot uses the excess control power to supply manual, pilot-induced damping. For the roll axis, however, the pilots would not accept low values of damping as satisfactory. For the pitch axis, these data show that for the minimum satisfactory control power increasing the damping does not affect pilot rating. The data for the roll axis indicate the effect of a sluggish airplane as the pilot requires increases in control power to accompany increases in damping.

Figures 5, 6, and 7 contain a circular symbol representing the amount of control power and damping which a machine the size of the X-14A would require if it were to satisfy the present military specifications for helicopters (ref. 6). Comparison of these required amounts of control power and damping with the boundaries defined in this investigation indicates that a fair agreement exists for the pitch and roll axes. For the yaw axis, however, the X-14A results indicate that the necessary control power and damping are much less than that required by the military specifications. The reason is, in part, that the military specifications require a high degree of damping for a small light helicopter, which would be sensitive to gust disturbances. This high damping requires a commensurately higher control power to obtain the maneuver capability desired. During these tests the pilots felt that the X-14A exhibited a high degree of hovering steadiness and an insensitivity to gust disturbances; thus, it did not require these large amounts of damping. Consequently, the pilots rated the lower amount of control power and damping as satisfactory.

Although the ranges of the control power and damping which could be investigated were less than that covered by use of the variable-stability helicopter and the angular motion simulator, the amount of control power and damping available was sufficient to obtain a pilot rating of 3, thereby covering the areas of greatest interest from the designers' standpoint. It was impossible, however, with the present setup to derive values for optimum control power about any given axis.

Comparison With Simulator Results

An investigation of the attitude control requirements of a hovering vehicle was conducted, using a piloted flight simulator, and the results are described in reference 2. A comparison between the boundaries determined in the simulator and those derived during this investigation is presented in figures 8, 9, and 10. On these figures the flight-determined boundaries have been shown as faired curves to aid the comparisons. The degree of correlation between the flight determined boundaries and the simulator boundaries varies for each aircraft axis. For the pitch axis, the 3-1/2 flight boundary correlates exactly with the single axis simulator boundary. For the roll axis the correlation is closest for the dual axes boundaries except that the 6-1/2 boundary again requires about twice as much control power for the same level of damping. The data for the yaw axis show poor correlation. The flight measured boundaries show that the pilot is willing to accept control power for a satisfactory rating much less than that indicated by the simulator.

The satisfactory rating of the yaw control power was unanimous by the 3 pilots. It should be especially noted that one of these pilots had participated in the simulator investigation of reference 2 while another had flown the variable-stability helicopter of reference 1. One possible explanation of the difference between the flight and simulator data might be that the pilots participating in the simulator tests had had primarily helicopter experience and no doubt interpreted the simulator response characteristics in this light. The simulator results may also have been influenced to some extent by the pilots' partial reliance upon an instrumentation presentation within the cockpit and by a task requiring yaw changes of a precise number of degrees. Some part of the differences between flight and simulator results can be due to differences in the mechanical control system characteristics.

CONCLUDING REMARKS

Questions that arise with any simulator data are also present in the flight investigation discussed in this report. Can the results obtained be extrapolated to other aircraft and in particular to larger VTOL aircraft? The application of the data to other vehicles will be influenced by the hovering steadiness of the vehicle. The present investigation was conducted on a deflected jet VTOL aircraft which is a very steady hovering machine, and is not affected by self-generated disturbances. When control power and damping requirements are considered for other types of VTOL aircraft, such as tilt wing or deflected slipstream (which past experience has shown to have a self disturbing nature during hovering), some adjustment to the boundaries should be made. In such a case, the boundaries derived in this report would represent maneuvering boundaries which indicate the control power and damping that should be supplied over and above the control power required to cope with these self-induced disturbances.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Mar. 12, 1962

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TABLE I.- PROPOSED PILOT OPINION RATING SYSTEM FOR UNIVERSAL USE

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter.

TABLE II.- PILOT'S RATINGS

Damping, 1/sec	Control power, radian/sec^2	Pilot ratings		
		Pilot A	Pilot B	Pilot C
Roll axis				
-2.85	0.80	6-1/2	---	---
	1.15	6	4-1/2	5-1/2
	1.65	5-1/2	3-1/2	3-1/2
	2.05	4	3	3
-1.95	.80	6-1/2	---	---
	1.15	5-1/2	4-1/2	4-1/2
	1.65	4	---	---
	2.05	3	3	3
-1.20	.80	5	---	---
	1.15	4	---	---
	1.65	3-1/2	---	---
	2.05	3	3-1/2	3-1/2
-.45	.80	6-1/2	---	---
	1.15	5	---	---
	1.65	4-1/2	---	---
	2.05	4-1/2	4-1/2	3-1/2
0	1.15	6-1/2	---	---
	2.05	6-1/2	---	---
Yaw axis				
-.95	.35	5	4	4
	.60	3	3	3
-.20	.35	7-1/2	4-1/2	5-1/2
	.60	4	3-1/2	4
0	.60	5	---	---
.10	.60	6	---	---
.15	1.0	6-1/2	---	---
Pitch axis				
-.8	.44	4	5	6-1/2
	.54	4	3-1/2	5-1/2
	.64	2-1/2	3-1/2	4
	.80	2	3	3-1/2
-.64	.80	2	---	---
-.48	.44	5	---	---
	.54	4	4	4-1/2
	.64	3	3-1/2	4
	.80	2	3-1/2	3-1/2
-.32	.64	3	---	---
	.80	2	---	---
-.15	.44	5	5	6-1/2
	.54	5	---	---
	.64	3-1/2	---	---
	.80	2-1/2	---	---
0	.80	3-1/2	---	---
.1	.80	5	---	---

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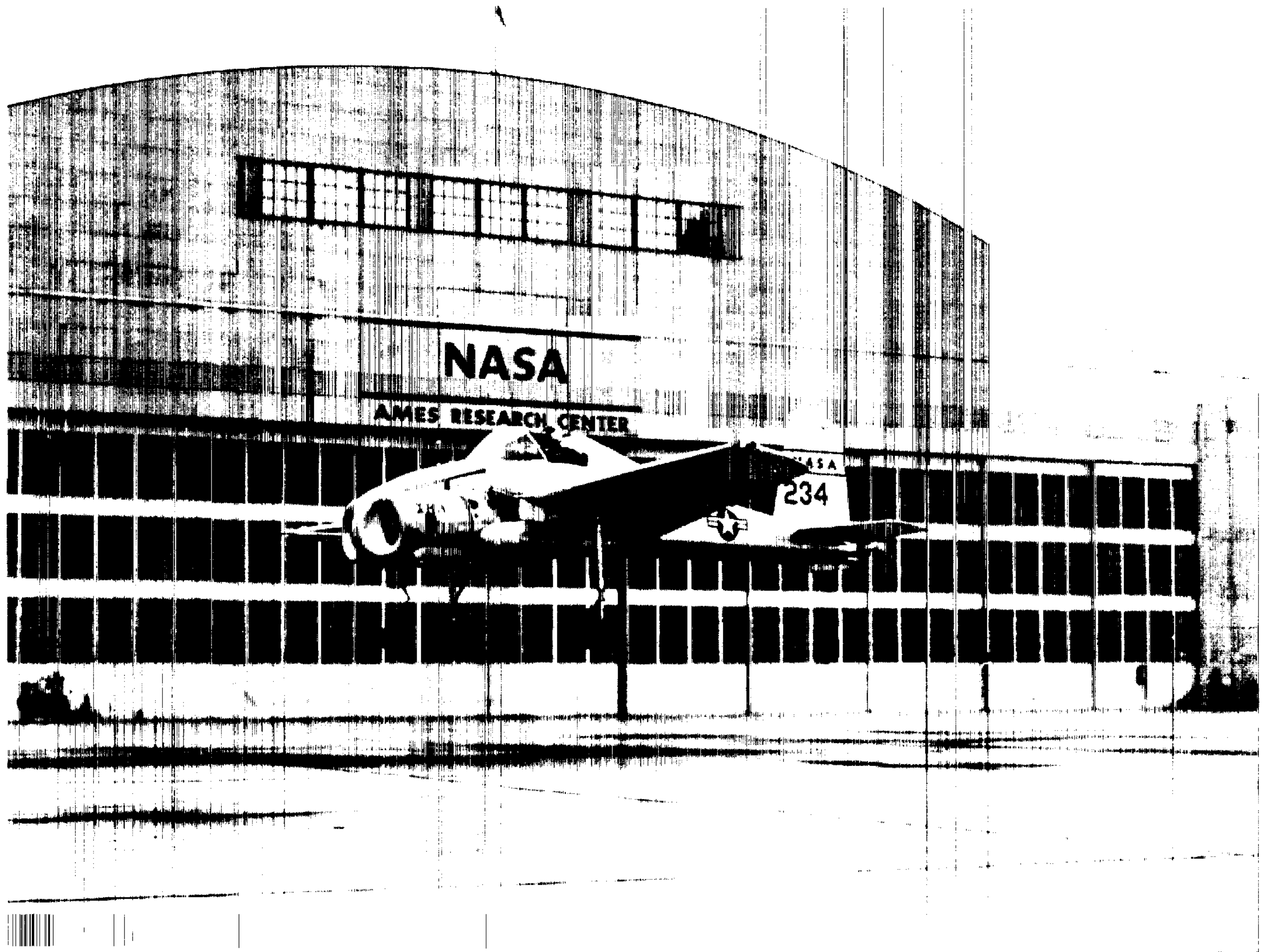

Figure 1.- Photograph of X-14A hovering in front of hangar.

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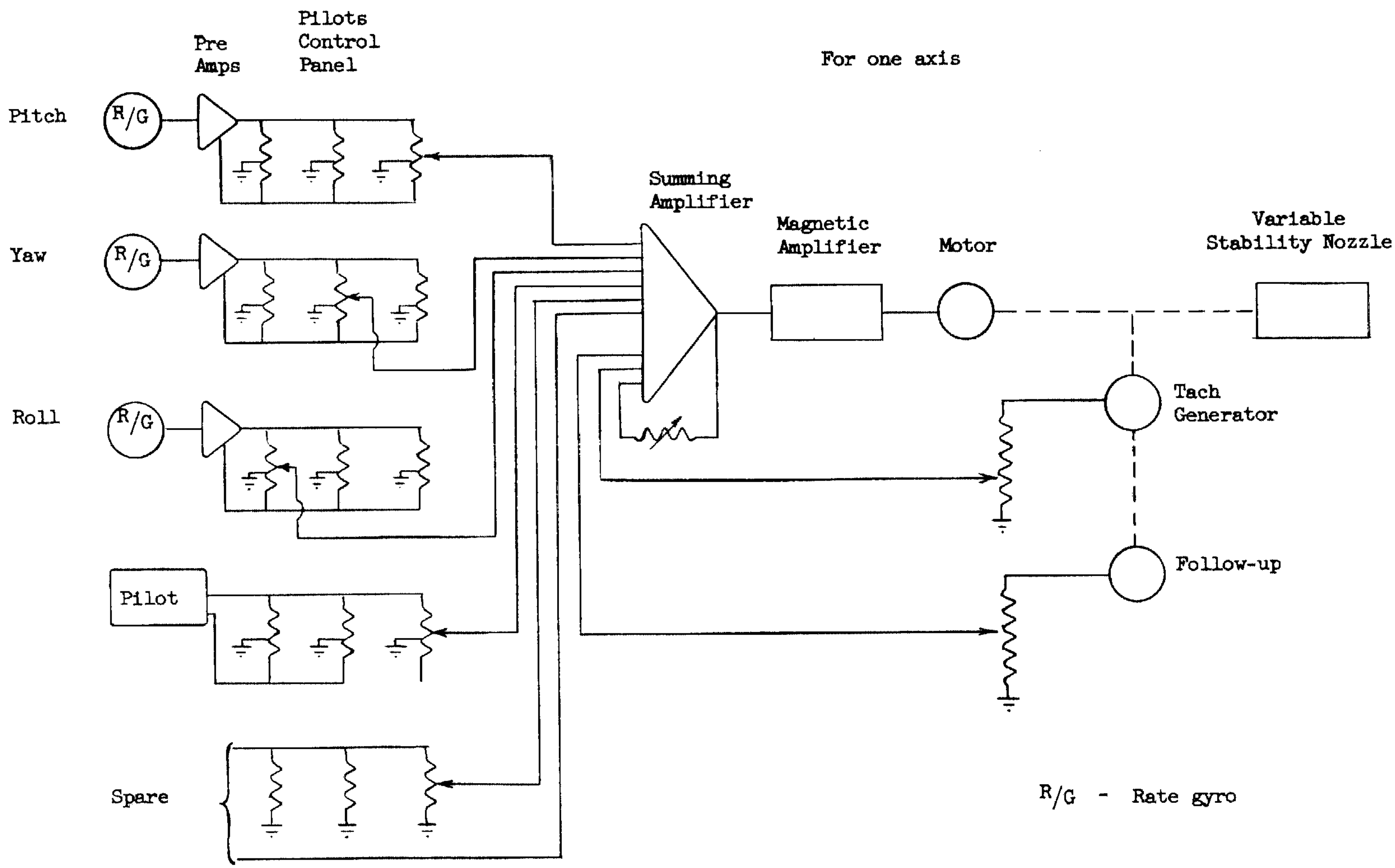

Figure 2.- Block diagram of variable-stability control system.

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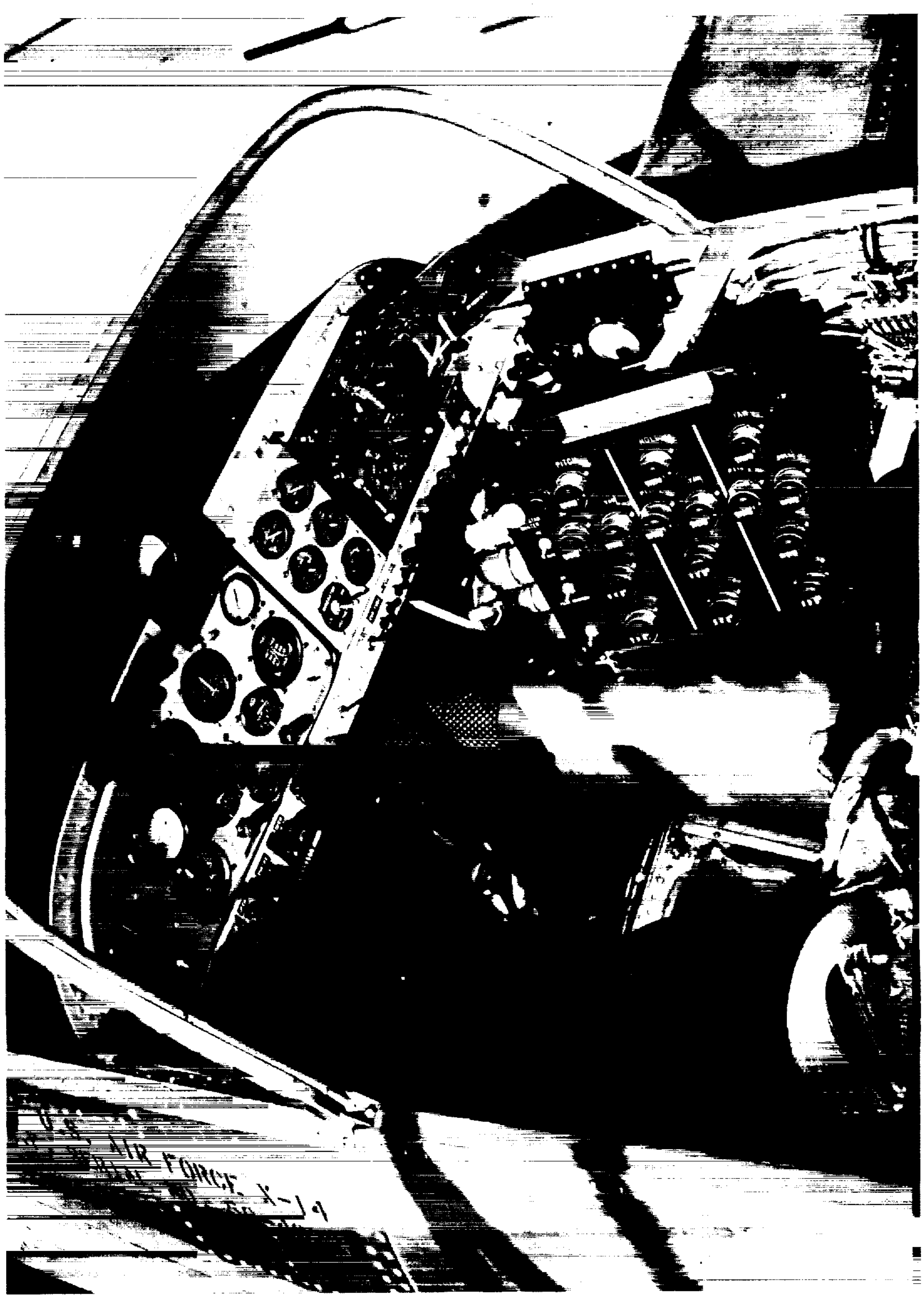

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Figure 3.- Pilot's variable-stability control panel in cockpit.

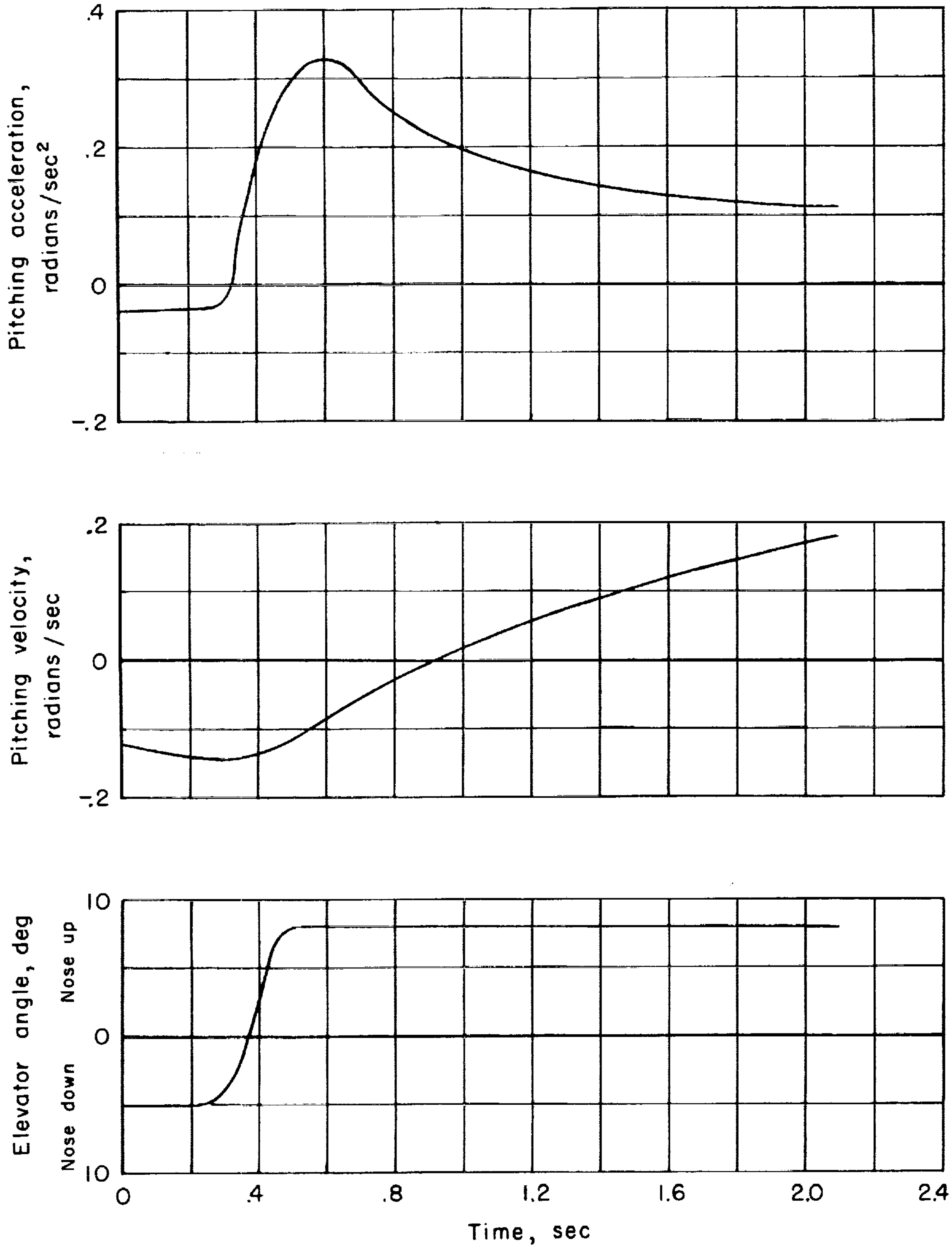

Figure 4.- Time history of a typical calibration maneuver.

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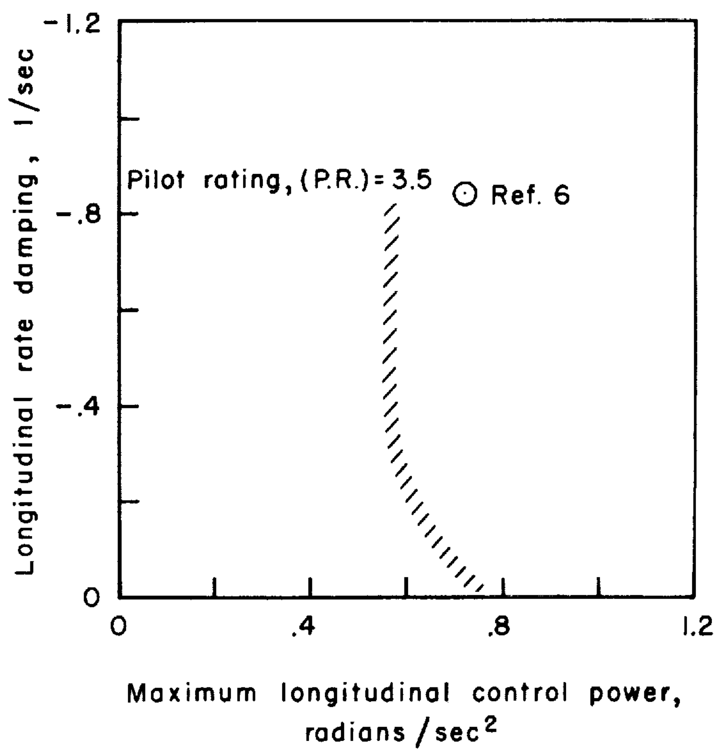

Figure 5.- Control power damping boundaries for the longitudinal axis.

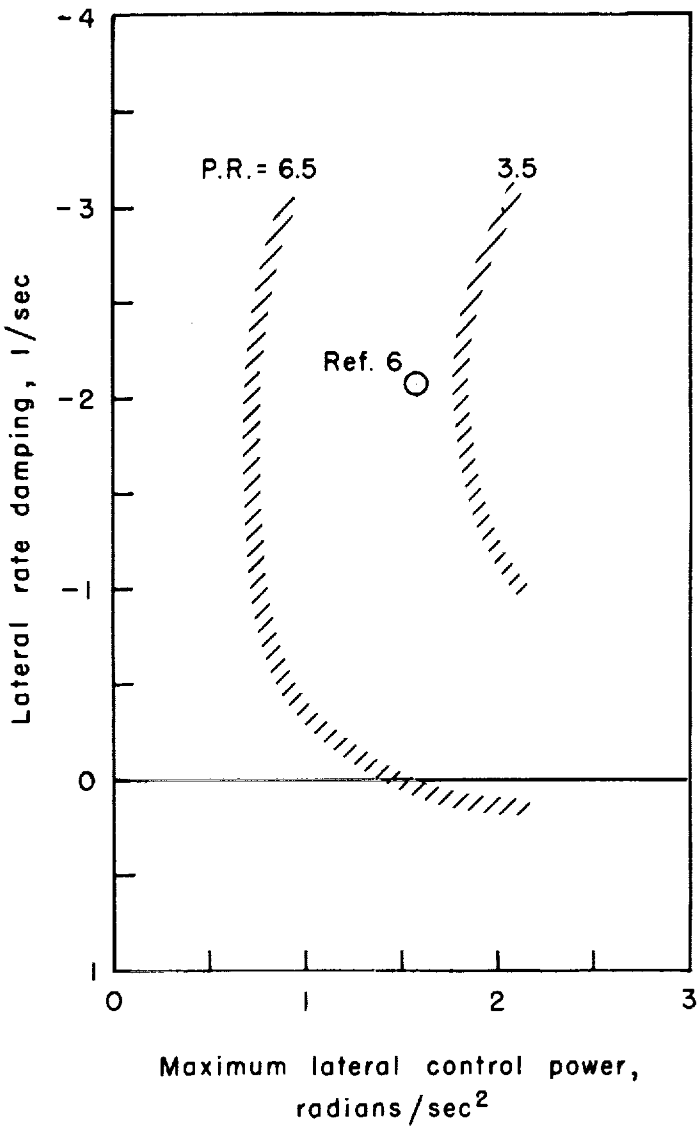

Figure 6.- Control power damping boundaries for the lateral axis.

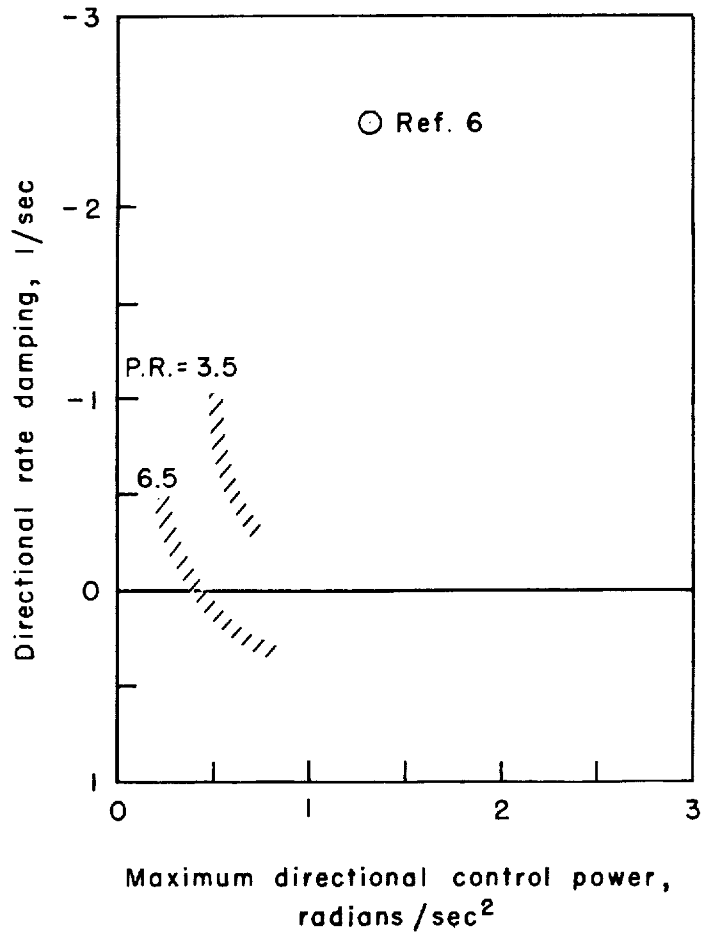

Figure 7.- Control-damping boundaries for the directional axis.

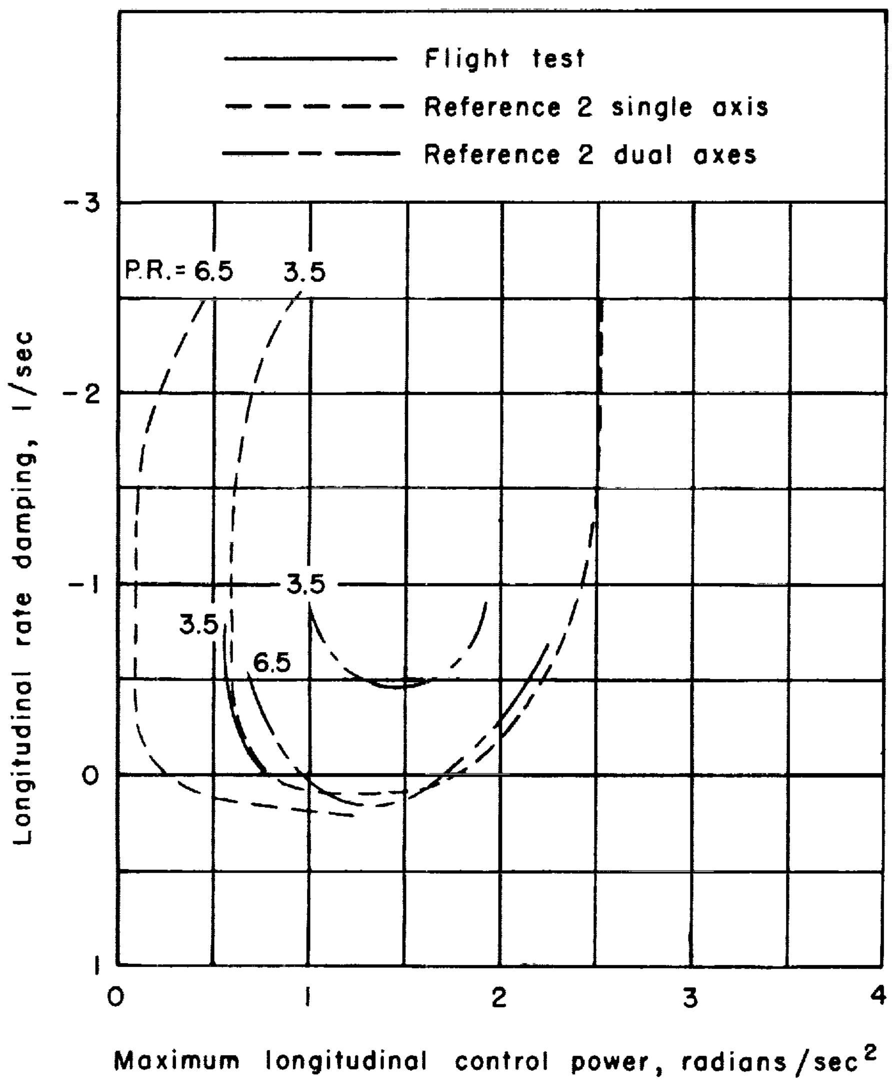

Figure 8.- Comparison of flight and simulator results for the pitch axis.

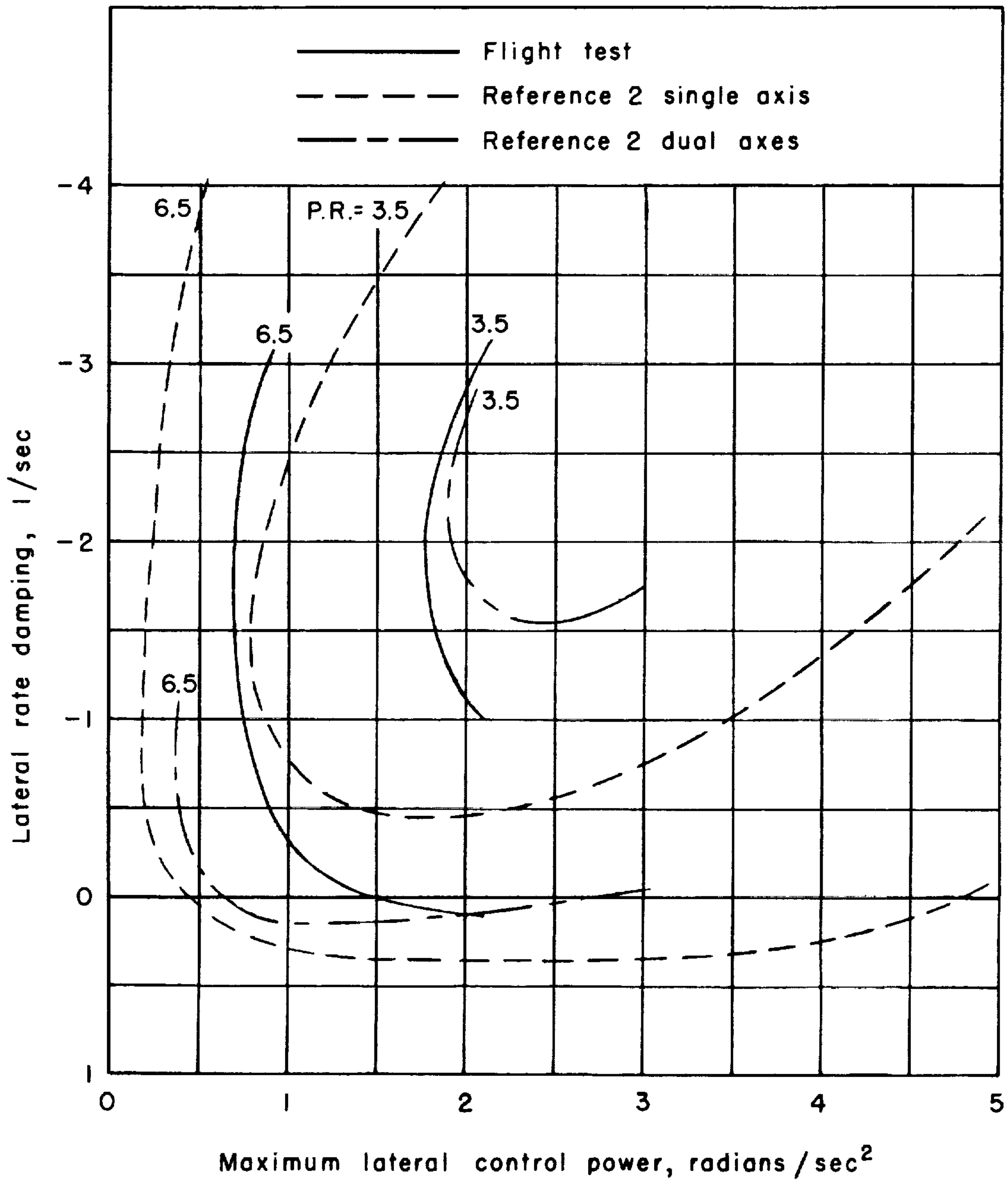

Figure 9.- Comparison of flight and simulator results for the roll axis.

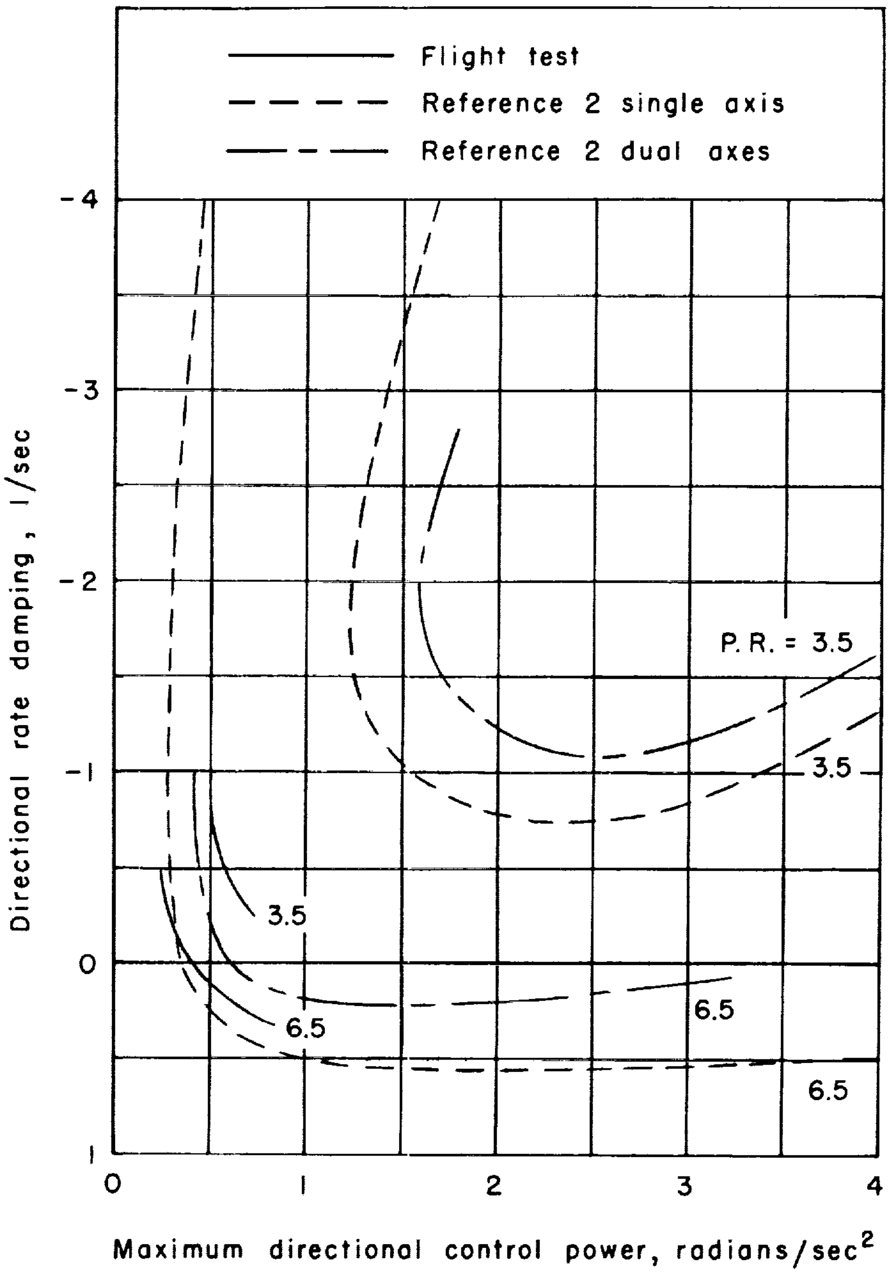

Figure 10.- Comparison of flight and simulator results for the yaw axis.

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3, Aircraft;
4, Aircraft safety and noise;
34, Piloting;
49, Simulators and computers;
50, Stability and control.)

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